# Most accurate drilling guidance by dead-reckoning using high precision optical gyroscopes

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**Abstract**

Drilling navigation by magnetic sensors has been for long the industry standard. In this paper an innovative approach is presented, using high precision optical gyroscopes.

When the natural or artificial magnetic field is disturbed by magnetic fields developed by high voltage electric cables or magnetized materials passing by, the drill-head orientation feed-back from the magnetic sensors is lost. At first this paper explains the limits of the accuracy achievable by magnetic sensors, used for drilling navigation

Drilling guidance needs a precise preparation. This paper introduces a modified minimum energy method, which generates a best fit polynomial for the desired drilling trajectory. This desired trajectory is compared with the actual trajectory polynomial. The guidance advice is generated by a novel line of sight method, which takes into account the constraints such as minimum bending radius.

The calculation of the actual drilling trajectory is done by dead-reckoning. This dead-reckoning is an old method, already used by the Dutch navigators on-board of the Duyfken of the East Indian Company. For the drilling a novel dead-reckoning algorithm is used giving a much better accuracy and allowing an in-situ calibration of the gyro system.

A sensor system based on advanced optical gyroscopes is presented in the paper. It allows real-time drill-head guidance and a continuous operation without any need to stop drilling for re-calibration or North seeking. It is shown on base of actual drilling cases, that a very high precision can be achieved, even for long drilling trajectories and in very difficult environment (electromagnetic fields, vibration and shock).

## Introduction

Precise navigation during Horizontal Directional Drilling (HDD) is needed for safety reasons and to achieve a sustainable use of the underground infrastructure. Since the introduction of the HDD trenchless techniques, a few decades ago, a lot of underground infrastructure has been installed.

For the drilling navigation and guidance mostly use is made of magnetic sensors ("magnetic steering tool") or a walkover locator. Both methods have certain disadvantages. The magnetic sensor uses the Earth magnetic field to measure the drill-head orientation. Sometimes also an artificial magnetic field is made by laying electric current transporting cables across the surfaces all along the drilling trajectory. These direct or alternating current carrying cables develop a known magnetic field, enabling to determine the perpendicular distance of the magnetic sensors from this cable. Due to the limitations of the magnetometers or flux-gates used to measure the magnetic field, a maximum accuracy in azimuth angle of 0.40 degrees is possible. Figure 1 depicts the internal structure of such a magnetic steering tool. The printed circuit board is installed within the non-magnetic tube (copper alloy). On the printed circuit board a tri-axis magnetic field sensing integrated circuit is installed, as well as a tri-axis accelerometer. The latter is used to determine the orientation of the sensing system to the Earth gravity field.

The magnetic steering tool, moreover only achieves the accuracy of 0.40 degrees in azimuth angle, when no disturbance exists of the Earth magnetic field. Many disturbances exist in urbanised areas, such as high voltage networks, ferro-magnetic materials and cathodic protection of underground piping systems. These disturbances can easily result in inaccuracies of many degrees.

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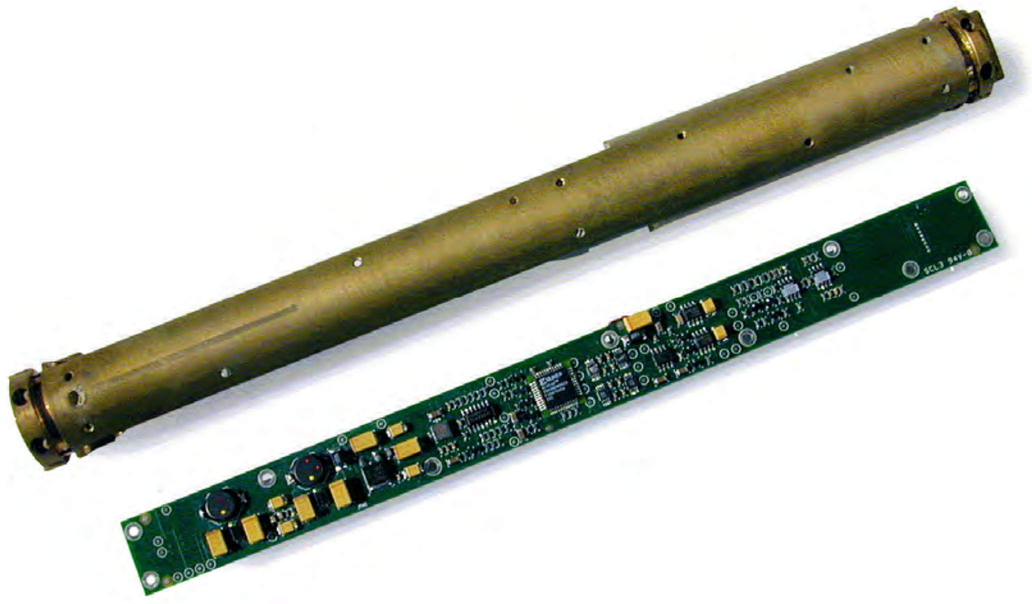

Figure 1. DrillGuide magnetic steering tool.

The walkover locator also has its limitations, as a degraded accuracy for increased drilling depth and the need for surface access above the drill-head.

The precise location was mostly tried to be determined by doing a survey after completion of the drill-job. For this surveying use is made of mechanical Dynamically Tuned Gyros (DTG). These gyro's have a small mass rotating at high speed. This mass directs itself at the tangential plane of the Earth to the geographical North. This survey only gives a limited accuracy, which is in the magnitude of the magnetometer system under ideal conditions, i.e. without disturbances of the Earth magnetic field. The result is a rather high degree of uncertainty about the location of underground infrastructure.

This paper presents a novel HDD navigation and guidance system. The cores of the system are optical gyros and an advanced so-called Kalman filter. This gyro steering tool (GST) system needs no surface access above the drill-head for laying of reference cables or access for measurement and it is continuously measuring, even when the drill-string is rotating at high rates. It has an accuracy even better than achievable by the survey methods after the drill-job has been completed.

## Navigation through underground

Above surface, since the NAVSTAR Global Positioning System (GPS) is fully operational (1994), navigation has become rather easy. However, in the underground, the GPS is not working. So the determination of the drill-head position needs other means of measuring. Since long, magnetic steering tools have been used. Whereas the magnetic steering tool has limited orientation accuracy, the gyro steering tool has a superb accuracy, allowing a close connection with the GPS positioning calculation methods.

A bore-hole trajectory has an entry and exit point. The position of these points is measured by the GPS in its most accurate execution (Differential GPS, Real-Time Kinematic) and the positions are given in the World Geodetic System rev. 1984 (WGS84). This system gives the position of the points in longitude, latitude and height. The GST measures the drill-head orientation with respect to the WGS84 frame. When local grid co-ordinates are used, these have to be transferred to the WGS84 system for precise measurement.

The bore-hole trajectory consists of circular and straight line segments. Where a circular / circular or a straight / circular connection exists, a bending point is defined.

The bending points also are defined in the WGS84 frame. When these bending points can be accurately measured during the pilot drilling, it gives the possibility to precisely map the underground infrastructure.

When the drilled bore-hole length is measured, for each distance the azimuth and pitch angle can be calculated from straight line and circular segments. In the ideal world the drilling engineer would then only have to steer the drill-head such, that the azimuth and pitch angles are as per calculation. However, in practice discontinuities exist due to soil conditions. Also the transfer from one bore-hole trajectory segment to another one not always can be followed. To overcome these problems a vector control approach is followed for steering guidance. Figure 2 shows the approach. The desired trajectory vector is calculated from the perpendicular difference between the desired and actual trajectory and ahead desired trajectory. This approach results in very smooth azimuth and pitch changes, which results in following the required bending radii.

The desired trajectory is calculated from the given entry, exit and bending points. A minimum energy cubic spline method is followed to calculate this trajectory. This calculation happens in the block “path planning” of figure 2.
Via an advanced dead-reckoning method the actual trajectory is calculated from the measured pitch and azimuth angles and the distance / speed of the drill-string. The planning gives the desired X,Y,Z vector, while the dead-reckoning module gives the actual X,Y,Z vector. These vectors are positional vectors, where “X” is the away axis, “Y” is the right axis and “Z” is the elevation axis.

The desired and actual vectors are compared in the “line of sight” module. This module calculates the optimum azimuth and steering angles for the actual X-position, such that the actual trajectory is followed as smooth as possible without causing too small bending radii. The steering corrections for following the desired trajectory are very small. This requires accurate measurement of pitch and azimuth angles.

The method requires very precise measurement of the azimuth and pitch angles. The accuracy is respectively:

- Azimuth angle measurement accuracy: +/- 0.02 degrees.
- Pitch angle measurement accuracy: +/- 0.01 degrees.

The modules of figure 2, which are in the large shaded area are software modules running in a surface situated computer. The optical gyro set is connected from down hole to the surface system via a transmission system, sending the roll, pitch and azimuth three times per second. This gives the drilling engineer a real-time feeling, when observing the display, while drilling.

The drill-string length is measured by a draw cable length measurement sensor. The cable of this sensor runs up and down with the drilling machine actuating cylinder or motor. In this way the drill-string stroke and speed can be real-time measured.

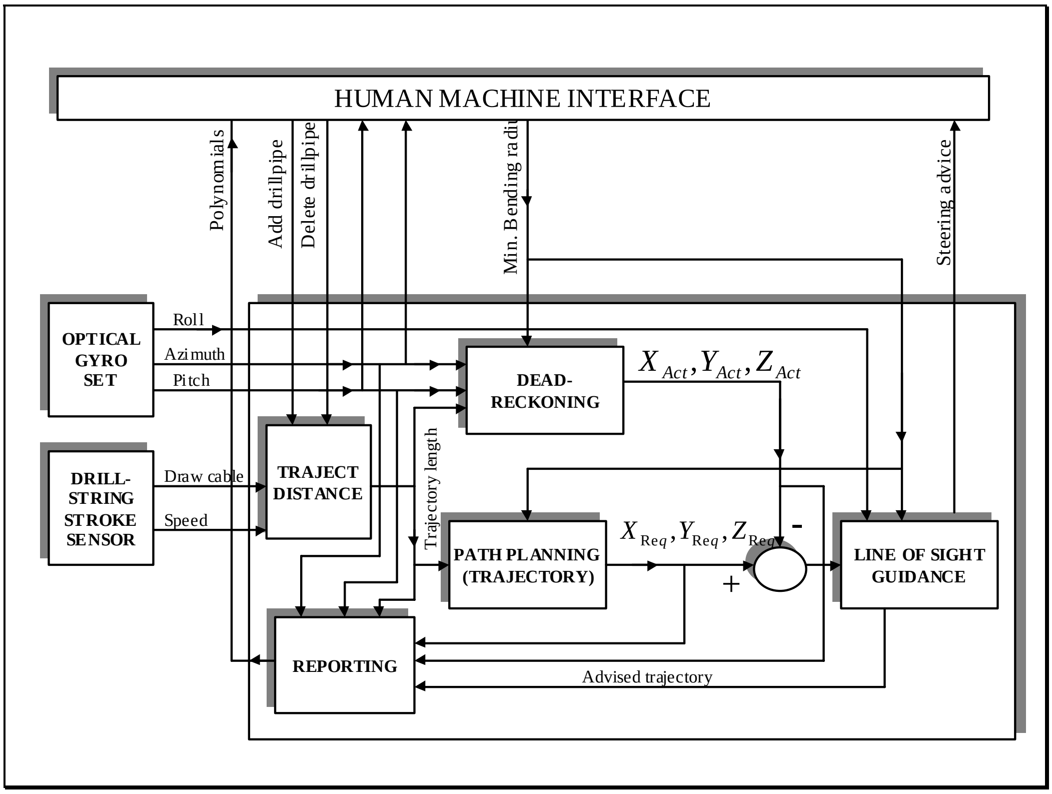


Figure 2. Block-diagram of drilling guidance by use of optical gyro's for navigation.

## Optical gyroscopes

To determine the actual position of the drill head in WGS84 coordinates without additional artificial information request, we have to know the pitch angle and the azimuth (angle of the drill head against true North) very accurately. The value of the local gravity of the earth is well-known (approx. 9.81 m/s²) and a tilt sensor can be used to determine the pitch angle of the drill-string if the drill head is at standstill. Unfortunately the drill head is not at standstill and every period of standstill reduces the efficiency of the drilling job – it is desired to drill most of the time to operate the drilling machine as economical as possible and not to wait to perform some measurements. Therefore it is necessary to determine the pitch and azimuth during the drilling (so-called Measuring While Drilling, MWD) and so tilt sensors cannot be used accordingly due to the high vibrations during the drilling.

To solve this problem to provide highest accuracy at minimum time of standstill, the here explained gyro steering tool system contains a full inertial navigation system (INS). The INS is specially designed to meet following parameters:

- small diameter (120 mm)
- high azimuth accuracy (0.02 deg)
- high pitch accuracy (0.01 deg)
- continuous drilling requirement; no request of periodic time consuming alignment at each new drill pipe insertion
- robust against vibration and shock
- high angular rate capability (200 $min^{-1}$, i.e. 1200 deg/s)

To meet these requirements, three optical gyros are used which are mounted perpendicular to each other to measure the angular rate vector in space. Optical gyros are working according to the relativistic Sagnac Effect, the advantage of this gyro technology is the independency of its measurements from vibration and shock because these gyros do not use any internal spinning mass but the photons of the light are used to measure the angular speed. Also three high accurate servo accelerometers are used to measure the motion of the drill head under dynamic motion / vibration. Gyro and accelerometer data are processed inside a so-called strap-down algorithm after digitization within a powerful signal processing unit to obtain azimuth, roll and pitch.

Knowing the local vector of the earth rate, which is automatically determined by knowing the local position (latitude, longitude, altitude) and the globally constant absolute value of the earth rate of 15.041 deg/hr (i.e. rotation of 360 deg per day due to 1 revolution per day around the earth's axis and 365.25 deg/year = 0.041 deg/hr due to 1 revolution of the earth around the sun within 1 year) the true North related direction of the drill head can be calculated using the gyro measurements and the pitch and roll determined from the accelerometers. After a ten minute initial North seeking procedure after power-on the system is ready for drilling and keeps the true heading accuracy due to the internally used Kalman filter algorithm. The advantage of the INS inside of the GST is to provide a very accurate solution despite of the high angular rotation of the drill string. This is done by special gyro scale factor error compensating methods which limit the angular error of the measurements to a value which is independent on the number of revolutions of the drill string over time. The Kalman filter allows to keep the true heading accuracy without loss of performance over time. A battery pack inside the drill head even allows power interruptions on the drilling machine without an impact of the system's accuracy. The next figure shows the structure of the inertial measurement system containing the gyros, accelerometers, the battery pack and the battery charger to survive power dropouts and the communication via the drill string to provide drill head information to the steering terminal with 3 measurements per second.

Measuring the true heading and pitch very accurately, the position of the drill head is measured by dead-reckoning. This method of position calculation is explained in the next chapter.

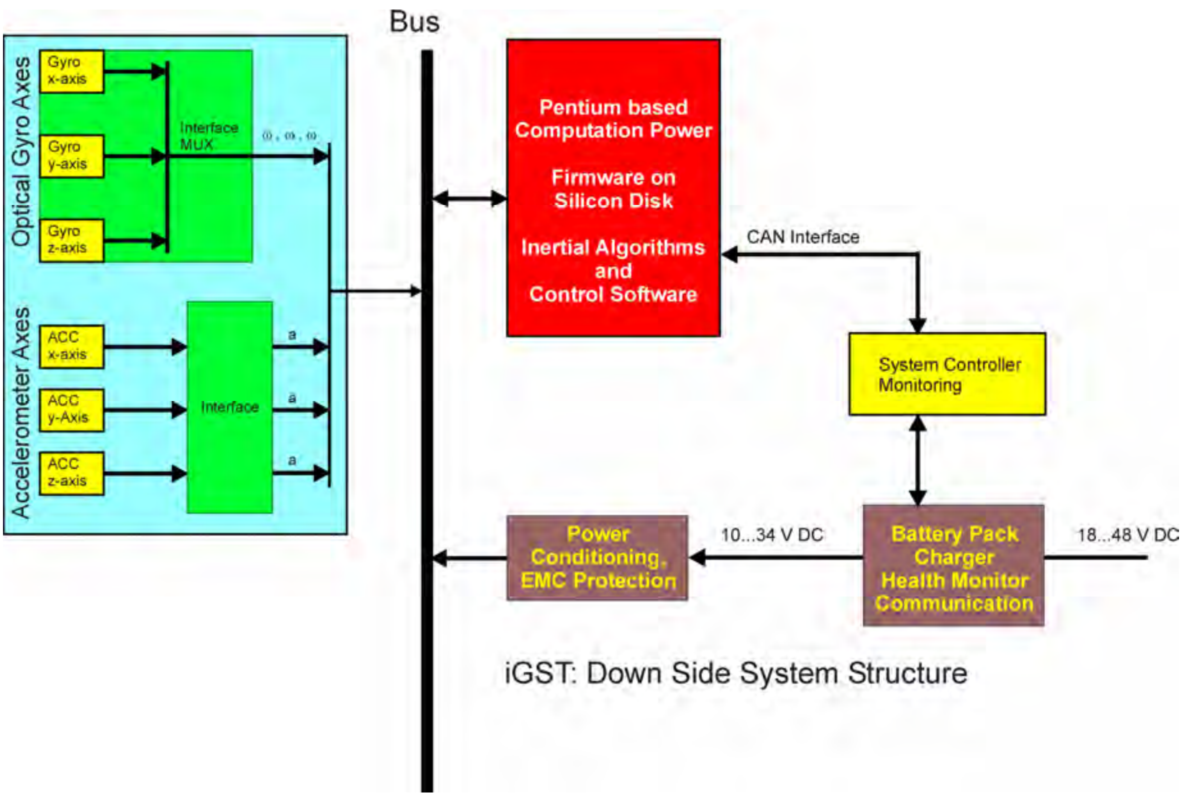


Figure 3. DrillGuide GST downhole system structure.

**Dead reckoning**

When Willem Janszoon as captain of the Dutch ship Duyfken discovered Australia in January 1606, he used the magnetic compass and the estimated ship speed to estimate the position of the Duyfken. The use of the measured speed and the heading at a flat sea gives the ship position. This method is called dead-reckoning.

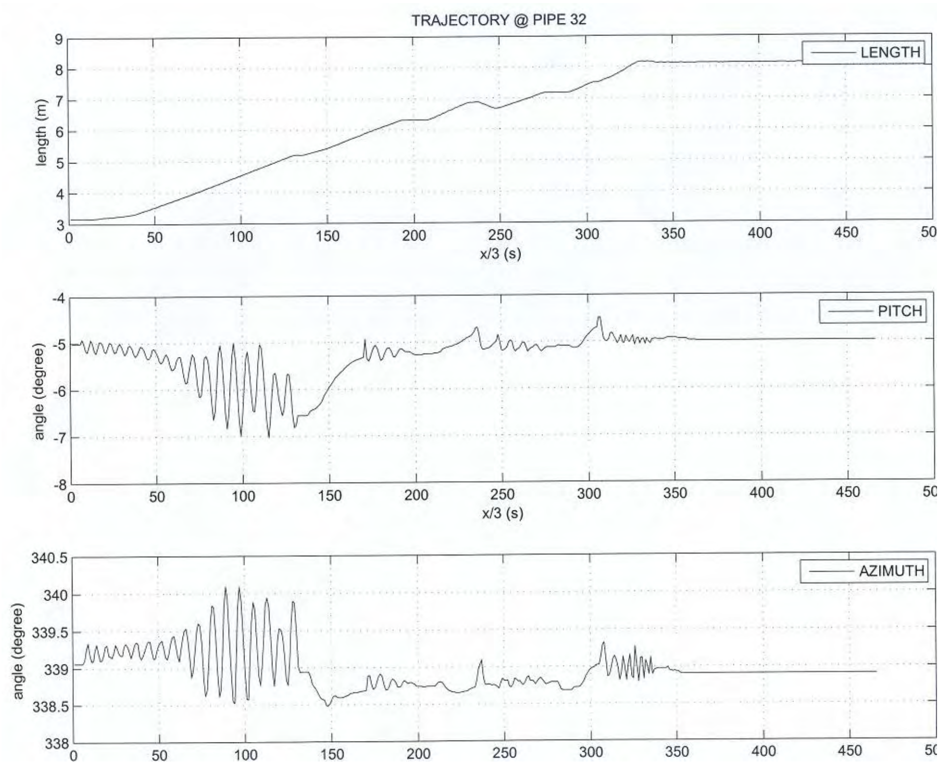


Figure 4. Oscillatory changes during drilling and steering actions.

Also for the estimation of the drill-head position dead-reckoning is used. In the days of Janszoon no computers existed. In wild seas it was difficult to use the dead-reckoning method. For dead-reckoning in drilling guidance the computer can smooth the wild excursions, which happen due to the drill-string dynamics. Figure 4 gives an example of the pitch and azimuth angle changes for the drilling length of one drill-pipe. Oscillatory motions of the pitch and azimuth angle are seen. The top graph shows the drill-string position in the away axis. When the rotation is stopped for steering the oscillations disappear.

Prior to do the dead-reckoning the signals are filtered to remove oscillatory and random pitch and azimuth angle changes, where the internal signal processing is performed with 2000 measurements per second to cover all dynamics. The result is extreme accuracy. Figure 6 shows the right axis deviation from the desired position for a 970 meter drilling. Deviations in the centimetre range are seen.

**Drilling guidance and user interface**

The user interface for the drilling engineer doing the steering at the drilling machine is of very big importance. The drilling engineer must be able to see the azimuth and pitch angle changes also while the drill-string rotates during the actual drilling. Only when this happens, a drifting in the right or elevation axis can be noticed in time. As can be seen in figure 4, the drilling will be stopped in time to execute steering actions. Figure 5 depicts a guidance display as is available for the drilling engineer within the DrillGuide GST system, who can always follow the process.

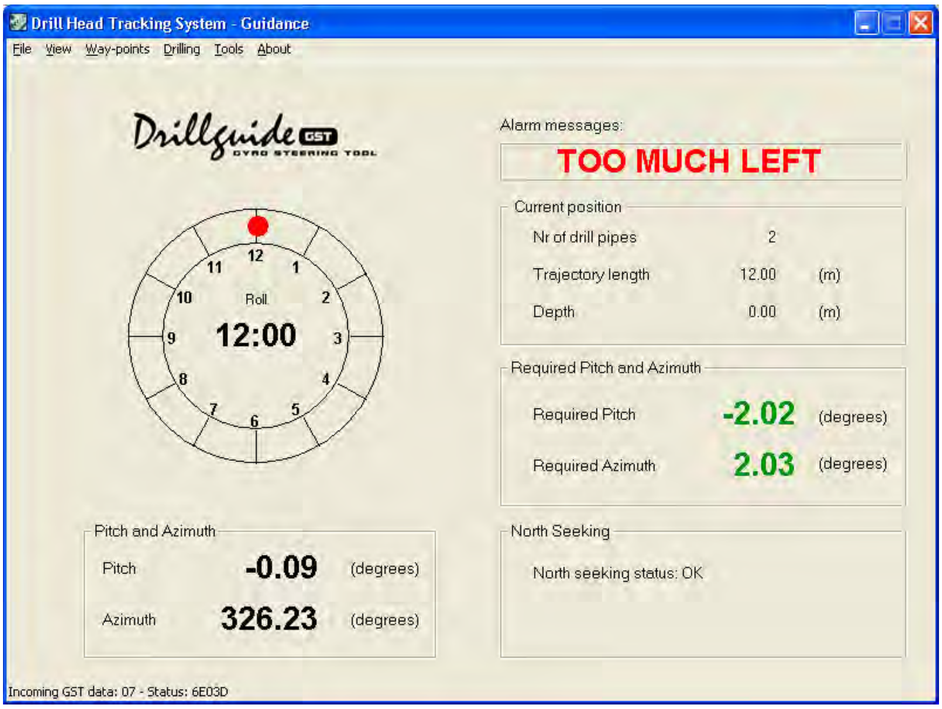


Figure 5. Guidance display of Gyro steering Tool (GST)

Despite of a very complex mathematics behind the data processing and filtering, the advantage of the mechanisation of the GST is that the operator does not feel all the calculations being made in the system – e.g. no parameter settings or system adjustments is required, so a very simple usage of a robust and high performance measurement system was the first design goal of the GST.

## Practical experience

The GST has been applied for various drill-jobs during the last one and a half year. At average, weekly two drilling guidance jobs were executed during this time. The deviation of the actual borehole trajectory from the desired trajectory typically was at maximum 30 centi-metres for a 700 meter long trajectory. Two typical jobs and the experience gained during those jobs will be explained:

### Crossing the IJ (Spring 2006)

The crossing of the IJ under water was a very challenging guidance job as after 970 meter of drilling, piles, which should not be touched, were present. Also it was not possible to make corrections at the end of the trajectory, because of very strict bending radii requirements. Figure 7 shows the water to be crossed at 50 meter depth.

Figure 6 shows the right axis deviation from the desired track. Due to drill-string dynamics and soil conditions along the trajectory deviations are seen. However, the dead-reckoning calculation is sufficient precise due to the precise azimuth and pitch angle measurement to steer the azimuth angle such that the desired trajectory is followed with the shown deviations.
After back-reaming a large gas pipe had to be pulled into the bore-hole. The precise radius of the bore-hole was of prime importance to keep the gas pipe stresses within limits. The accurate measurement of azimuth and pitch allows for very precise steering, which results in precise bending radius control.

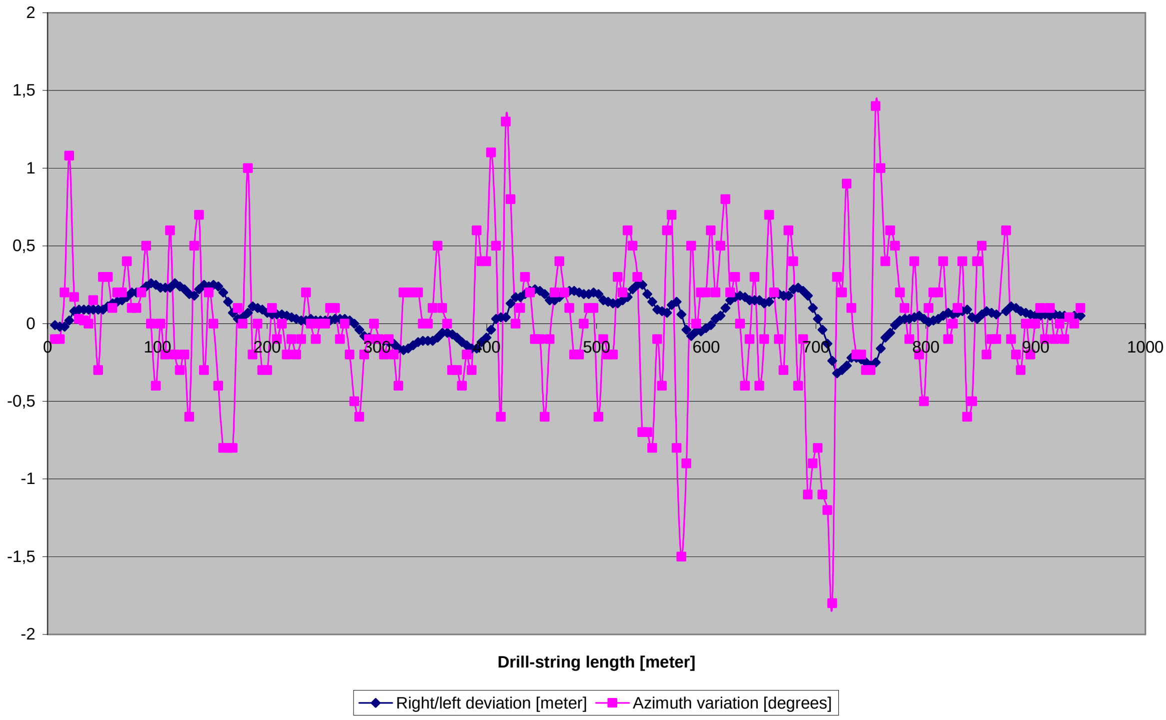


Figure. 6. Cross track deviations during the 950 meter IJ crossing.


Figure 7. IJ crossing with length of 970 meters at 50 meters drilling depth.

**Crossing Railroads (Summer 2005)**

Figure 8 shows a railroad yard. The crossing with conventional navigation tools was not possible due to the fact no access at the rails was allowed for safety reasons. Also magnetic steering tools could not be used due to the tremendous disturbances of the Earth magnetic field by the rails and high voltage cables above the railroads.

The GST right axis and elevation axis deviation from the desired trajectory over the 700 meters trajectory was kept within 25 centimetres.

The drilling below the rail road showed the safety aspects, when being able to accurately measure while drilling. A later drill-job at a refinery and a drilling very close to very high voltage cables proved this. The drilling engineer can immediately see, that the trajectory is not followed and consequently stop to steer.

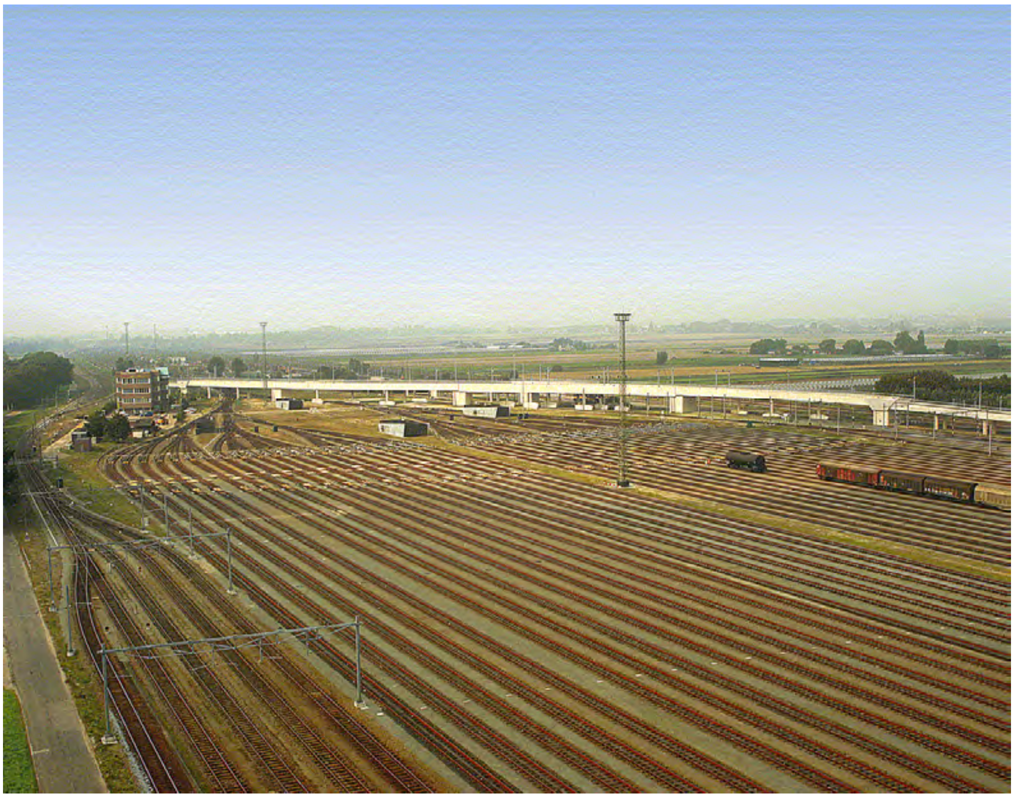

Figure 8. Crossing the railroads at 20 meter depths over 700 meters.

## Conclusions and recommendations

The accuracy of pilot drilling of HDD operations can be drastically improved with a highly accurate drill-head orientation measurement system. The accuracy of the measurement of azimuth and pitch allows very precise drilling, such that precise bending radii can be made. Further details can be found at www.drillguide.com

Advanced signal analysis method and the addition of extra sensors in addition to the optical gyro's, such as the measurement of the drill-string stresses (bending magnitude and direction, measured by strain gauges) can further improve the accuracy and the steering advice.

The line of sight controller can be further extended with additional sensors, such as mud pressure measurement and obstacle detection. Objects in front of the drill-head can be detected by the use of active magnetic fields developed in the drill-head. This object detection in conjunction with the presented minimum energy planning and dead-reckoning smoothing algorithm opens the way to semi- or full-automatic drilling.